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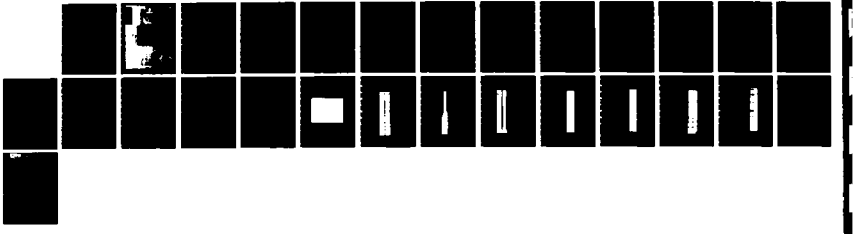

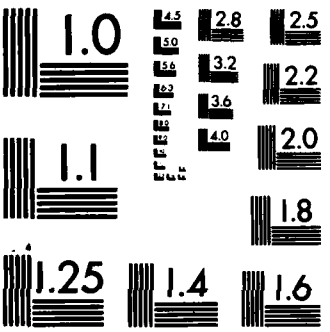

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Report

SPECTRAL MONITORING OF ARGON-TUNGSTEN
ARC WELDING OF 6-4 TITANIUM
TO DETECT THE PRESENCE OF AIR

(Contract No. N00014-80-C-0754)

to

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
Arlington, Virginia

December 8, 1982

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TOPICAL REPORT

on

SPECTRAL MONITORING OF ARGON-TUNGSTEN ARC WELDING OF 6-4 TITANIUM TO DETECT THE PRESENCE OF AIR

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Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

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SPECTRAL MONITORING OF ARGON-TUNGSTEN ARC WELDING OF 6-4 TITANIUM TO DETECT THE PRESENCE OF AIR

by

R. W. Hyatt, O. A. Ullrich, and H. W. Mishler

INTRODUCTION

The need for careful shielding of the molten weld puddle from air when welding titanium is well known. Molten titanium has a very high solubility for oxygen and nitrogen, and the solution of small amounts of these gases will embrittle the titanium weld. Unfortunately, there is currently no reliable method for nondestructively determining whether oxygen or nitrogen is being picked up by the molten metal during the welding operation. The color of the weld is used as a measure of detecting surface contamination that may occur as the solidified weld cools. If the surface is not protected during cooling, coloration from light straw to gold to light blue to deep blue will occur depending on the degree of surface contamination. However, this coloration is not a reliable quantitative method for detecting contamination of the molten weld metal.

Pure argon is used to shield the arc and molten titanium weld pool. A small amount of air can enter this shield due to various causes, e.g., disruption of the gas shield by strong air drafts, entrainment of air due to turbulent argon flow, or air entering the argon line through leaking fittings. A method of detecting the presence of air and, preferably, measuring its content would provide a means of quantitatively monitoring the shielding-gas quality. A spectroscopic monitoring system appears capable of filling this need. This report describes research conducted to evaluate the practicality of spectroscopic monitoring.

In investigating the possibilities of such a system, aspects which must be evaluated include:

1. Is the presence of nitrogen and/or oxygen detectable in the presence of a great excess of argon and other elements present--titanium, aluminum, vanadium, tungsten, plus possible impurities such as silicon, sodium, and carbon?

2. Can such a detection system be sensitive enough to be useful?

3. Can a rugged, sensitive and quickly responsive system be adaptable to the industrial welding environment and be economically feasible?

The first two of these questions have been addressed in detail in the work reported here; the third is discussed but not fully answered.

SUMMARY

The research reported here was undertaken to determine if low concentrations of air at the arc can be detected during welding by spectroscopic methods. If practical, this technique could form the basis for an in-process system for monitoring the gas shield quality when welding titanium.

The method studied involves detecting the presence of nitrogen or oxygen in the arc by detecting lines of these elements in the optical spectrum of the arc during welding.

Using a grating spectrograph of 3/4-meter focal length, many lines of nitrogen and several lines of oxygen were detected in the

spectrum of a 100-amp tungsten-argon arc struck against a clean block of 6-4 titanium. The optical spectrum from 3500 to 8700 Å was studied, and at three regions--centering at 5226 Å, at 8216 Å, and at 8683 Å--relatively isolated lines or groups of lines caused by the presence of air in the arc were identified.

The spectral lines in these regions are widely enough separated from lines present in the air-free spectrum that a practical means of real-time monitoring of air in the arc seems readily achievable. Thus, the continuation of this exploratory work is strongly recommended. Work in the next phase would consist of: (1) selecting the wavelength region most adaptable to the monitoring requirements, (2) identifying and procuring, or having made, narrow-pass-band optical filters which would most effectively separate and transmit the selected wavelengths, (3) select an appropriate photosensor, (4) devise a suitable electronic circuit to convert the photosensor signals to a meter or other suitable output indicator, and (5) based on the results of these steps, assemble a breadboard device whereby the operability of this arc-monitoring concept would be demonstrated in the welding laboratory by adding known, small percentages of air to the argon in an operating argon-tungsten titanium welding apparatus.

BACKGROUND

In addition to the well-developed science of spectroscopy as a broad base for the monitoring concept investigated in the research reported here, numerous studies have been published on the spectroscopic properties of various forms of gas-tungsten welding arcs.

Materials emit optical radiation when electrons which have been excited to some higher energy state return to a lower state. In the welding arc, means of exciting electrons include both the voltage applied to maintain the arc and the temperature of the arc. By far, the more important of these is the very high temperature of the arc. Further, the energy applied to the atoms and molecules of the materials present in the region of the welding arc is sufficient not only to

excite electrons, but to ionize atoms by the removal of one or more electrons. Thus, the greater the energy applied, the more lines will be present in the spectrum of radiation emitted from the arc.

Temperatures of 30,000 K and higher have been reported[1-6] for welding arcs operating at roughly 10 volts DC and up to 500 amps. This temperature is high enough that triply ionized nitrogen and argon ions can be observed.

Figure 1* shows the number of various atom and ion species as a function of temperature for argon and nitrogen as calculated by Busz and Finkelnburg.[1,2] Temperature distributions in arcs of the GTA process have been given by various references,[1-5] and a recent reference[6] indicates that, within 0.040 in (1 mm) of the tungsten cathode, temperatures higher than 20,000 K may occur in a 100-amp arc. Thus, one might expect to observe spectral lines in both argon and nitrogen of not only neutral and singly ionized species, but of doubly ionized ions as well.

Quigley[4] has demonstrated that the main body of the gas-tungsten arc, consisting almost exclusively of gas ions, emits lines characteristic of the gases only; lines of the metallic elements appear only very close to the anode surface. Tungsten lines probably are present, but are hardly detectable compared to argon and titanium. Consequently, the vast preponderance of the radiation emitted by the arc is from argon, spectral lines of this element being strong and, with the exception of the mid-6000 Å region, distributed abundantly and more or less uniformly throughout the spectral range from 3500 to 8700 Å.

EXPERIMENTAL WORK

Apparatus was assembled whereby measured concentrations of air could be added to the argon used as the shielding gas and spectra of arcs both with and without the air contaminant were made over the range from 3500 to 8700 Å.

---

* Figures 1 through 10 and Table 1 begin on page 13.

Preliminary Work

In preliminary work, reducer valves, flow-control valves, flowmeters and a mixing chamber were assembled whereby measured percentages of air, filtered from the Institute's compressed air supply, could be added to high-purity (99.995 percent) argon. The pressures of both gasses were set, individually, for 20 psi at zero flow rate; the flow rate then was set at 30 cu ft/hr. The gas used during the tests was set for air percentages ranging from 0 to 5 percent.

Further, a block of alloy titanium (Ti-6Al-4V), 2-1/2 by 7-3/8 by 17-3/8 inches, was mounted on a linear-traversing carriage set for a speed of about 8 in/min and passed under the stationary arc. Welding parameters were: current of 100 amps, arc voltage of 8.9 v, and arc length approximately 3/32 inch. The 3/32-inch diameter, 2 percent thoriated tungsten electrode protruded 3/32 inch from the 3/4-inch ID (No. 12) gas cup. The tungsten electrode was sharpened to an included angle of about 20 degrees and the tip very slightly flattened to a diameter of 0.01 inch.

By simply passing the titanium block under the arc, with no metal being added, melted beads were made on the block surface with pure argon and with 0.7, 1.1, 1.4, 2 to 3, and 5 percent of air mixed with the argon. Inspection of the beads showed, by the appearance of the colored, optical-interference TiO_2 layers, a gradual increase in thickness of the oxide layer until, at 5 percent air, a white powdery deposit of TiO_2 was present. It was judged by experienced welders that 3 percent of air would be about the maximum permissible for a dependable, satisfactory weld. Consequently, to determine that the monitoring method being investigated had the necessary sensitivity, an air concentration of 2 percent was used for most of the spectral tests. One run was made at 1/2 percent air. Gas-delivery lines were thoroughly purged before striking the arc and making each exposure.

Apparatus and Procedure for Recording Spectra

Figure 2 is a sketch of the apparatus used to record spectra. It shows that radiation from the arc passed through filters, reflected from a mirror and irradiated the spectrograph slit, with no focusing optics in the beam. The cumulative beam path from arc to slit was about 19 inches. The spectrograph was a SPEX Model 1800 Combination Spectrograph-Spectrometer with a focal length of 3/4 meter.

To record the wavelength-reference spectra, the mirror was removed so that radiation from a small mercury discharge lamp could enter the slit. For each run, the spectra of the arc, with and without air were recorded side by side, with a mercury spectrum recorded above and below the arc spectra so that exact wavelength reference points could be marked on the arc spectra.

Different sensitivities of the photographic recording media at different regions of the spectrum required the use of neutral-density (Kodak Wratten) filters of different densities as well as different durations of exposures to get spectra of good quality. Polaroid Type 52 (ASA speed 400) film was used for the spectral region from 3500 to about 6500 Å; Eastman Kodak High-Speed Infrared Film, Type 4143, was used from 5700 to 8700 Å, including some overlap with the Polaroid film.

Glass filters of various spectral absorbing properties were used in the various spectral ranges to permit radiation from only the range being recorded to fall on the photographic plate. If these filters were not used, second and third-order spectra of shorter-wavelength radiation from the arc would fall on the photographic plate, thereby producing spurious lines and making interpretation of the spectra unnecessarily and probably impossibly complicated. A filter of window glass was used in the range from 3500 to 5100 Å. A yellow-glass filter--Corning No 3385, which absorbs radiation of wavelengths shorter than 4700 Å--was used in the range from 5100 to 8000 Å. A red filter--No 259, which absorbs radiation of wavelengths shorter than 6300 Å--was used in the range from 8000 to 8700 Å.

Exposure times ranged from 1 to 16 seconds. The spectrograph slit was set at 0.008 in (0.2 mm), and its length was 0.2 in (5 mm). The width of the image of the slit on the film is the same width as the slit.

The arc was produced by a Linde Torch, HW 27, Machine Barrel, Cyclamatic, Model 266, AVC.

Figure 3 is a photographic print of a typical set of spectra. Because the spectrograph spreads the spectrum out much longer than the length of the photographic film, in order to provide the necessary resolution, the complete spectral range studied in this work was covered in seven steps with the following approximate ranges: (1) 3650 to 4350 Å, (2) 4350 to 5100 Å, (3) 5100 to 5800 Å, (4) 5800 to 6650 Å, (5) 6650 to 7400 Å, (6) 7400 to 8100 Å, and (7) 8100 to 8700 Å. Resolution was about 1.7 Å.

The small mercury glow lamp that provided the wavelength reference spectra contains a small amount of argon to assist in starting the glow. Thus, argon lines show in some of the mercury spectra. A more complete set of reference lines was made available by using the second- and third-order spectra of the strong, shorter-wavelength mercury lines, and not using the colored-glass filters described above. (These are indicated by the notations, for example, 2 x 4339.23 Å (= 8678 Å), under Hg 8678 Å in Figure 10.

RESULTS

Figures 4 through 10 show the spectra from the seven ranges, with various lines in the various spectra identified. These show mercury reference spectra, welding-arc spectra with argon shielding gas only (identified as "no air"), and spectra of the same welding arc but with 2% of air added to the argon shielding gas.

In two ranges, no additional lines are present in the spectra with 2% air added, namely in Figures 7 and 8, covering the range from 5882 to 7384 Å. In other ranges, numerous additional lines are present, attributable for the most part to nitrogen in various states of ioniza-

tion. Some of the additional lines are attributed to oxygen, as in Figure 5.

These lines were identified by measuring their positions using a traveling microscope, comparing these positions with the position of mercury lines in the adjacent spectra and calculating the wavelengths. In most cases, prominent argon lines were identified and then used as a more refined internal calibration source to identify more certainly other, weaker argon lines, titanium lines, and, finally, the nitrogen and oxygen lines. Standard reference tables[7,8,9] were used in ascribing elements to lines in our spectra. Because the materials present in the arc environment are either very pure, fairly pure, or present in relatively low concentrations, the following are the only elements expected to produce spectra: argon, nitrogen, oxygen, titanium, aluminum, vanadium, tungsten and thorium.

Question marks in these figures indicate uncertainty in the identification of the element causing the line so marked.

Although many additional "air" lines are present in some spectral ranges, e.g., Figures 4 and 9, they are either so weak or so close to other non-air lines that they would not be usable as monitoring lines.

The ranges in Figures 5, 6 and 10 offer lines of interest and possible practical use for monitoring, because they appear reasonably strong and are located possibly far enough from other non-air lines that some sharp-cut optical filter might be used to isolate them in a practical monitoring device. These lines are identified in Table 1 and deserve close study.

The phenomenon of quenching is readily observable in most of these figures as evidenced by the marked weakening of the intensity of many argon lines in the presence of air. For example, note Ar 8264.52 and ArI 8667.94 in Figure 10 or ArI 6965.43, ArI 7067.22, and ArI 7272.93 in Figure 8.

One set of spectra also were made with 1/2 percent air in the spectral range 8014.79 to 8718.84 Å of Figure 10. The set of nitrogen lines 8680.27 to 8686.16 still are present, although, of course, much

weaker. However, they appear strong enough that they probably would actuate a monitor. Quenching also is observable in this 1/2-percent-air spectrum, although much weaker as well.

DISCUSSION

A number of lines of the nitrogen spectrum and possibly a few lines of the oxygen spectrum have been identified as being sufficiently isolated from lines of other elements--primarily argon and to a much lesser extent titanium, vanadium, aluminum, and tungsten--that they offer good possibilities of providing the desired indication of air in the titanium-welding arc.

The most isolated line is one at about 5226 Å, possibly due to quadruply ionized nitrogen (i.e., N IV), because its nearest interfering lines are about 40 Å distant on the short-wavelength side and perhaps 20 Å distant on the long-wavelength side (Figure 6).

A set of lines of interest ranges from 8680.3 Å to 8718.84 Å, with the nearest interfering lines being 12.4 Å distant on the short-wavelength side and more than 22 Å distant on the long-wavelength side.

Isolation of these and other nitrogen or oxygen lines from interfering background lines which lie even closer than noted above, can readily be accomplished with a spectrograph of the type used in this study as demonstrated in Figures 4 through 10. However, this instrument is far too large, heavy, delicate, and expensive to be used as an arc-monitoring tool in the field. A practical field-use device would preferably be small, rugged, reliable, easy to operate, and moderate in cost. Although a simpler prism or grating spectrograph might fulfill the above requirements, a simpler but highly effective approach to providing the spectral isolation required is by means of special interference-type optical filters. The specific design of filter used would depend on the spacing of the monitored line from adjacent background lines.

In a basic concept, an arc monitor would consist of a small box, perhaps a 3-inch cube, with a filter as an entrance window which

would exclude all radiation except that in the spectral band occupied by the selected nitrogen or oxygen lines. A photosensor would detect the presence of radiation transmitted and signal some indicator. Numerous variations and refinements are possible. One variation might involve a second optical-sensor channel which transmits radiation in some band that does not change whether air is or is not present in the arc. This would act as an intensity reference against which the radiation due to the presence of air is photoelectrically compared. A further refinement might make use of an argon line which is shown to quench in the presence of air. With this quenchable radiation as the reference, greater sensitivity would result because the ratio of air radiation to argon radiation would change faster than in the above case. The use of sensors that also are spectrally selective would minimize background radiation and improve both stability of operation and sensitivity.

The spectral range from 8680.27 Å and 8718.84 Å appears particularly attractive because of the availability of stable sensors but procurement of sufficiently selective spectral filters may be a problem.

CONCLUSIONS AND RECOMMENDATIONS

Based on the research results of this project on titanium-arc monitoring, it is concluded that the proposed approach of optically detecting the presence of air in the arc is sound and could be pursued to a practical monitoring system and device. This conclusion derives from the facts that:

1. Several bands of fairly well isolated nitrogen and oxygen spectral lines are present in an air-contaminated gas-tungsten arc.

2. These bands are readily detectable, at least photographically, at concentrations of air in the argon below that which would cause a defective weld.

3. Some lines are photographically detectable at concentrations between 1/5 and 1/10 of those which would cause a defective weld.

4. Commonly available today are photosensors and ancillary control and amplifier circuits which should have adequate sensitivity to detect these oxygen and/or nitrogen lines and thereby facilitate the desired monitoring function.

5. If narrow-passband filters are not available off the shelf, common technology could produce them.

6. As presently conceived, it should be possible, and practical, to make an arc monitor which is small, light, rugged, sensitive, reliable, and economically attractive.

It is recommended that work on arc monitoring be continued with the objective of designing and assembling a breadboard arc-monitoring device to demonstrate operability of the concept and evaluate sensitivity. Work would consist of: (1) selecting the wavelength region most adaptable to the monitoring requirements, (2) identifying and procuring, or having made, narrow-passband optical filters which would most effectively separate and transmit the selected wavelengths, (3) select an appropriate photosensor, (4) devise a suitable electronic circuit to convert the photosensor signals to a meter or other suitable output indicator, and (5) based on the results of these steps, assemble a breadboard device whereby the operability of this arc-monitoring concept would be demonstrated in the welding laboratory by adding known, small percentages of air to the argon in an operating argon-tungsten titanium welding apparatus.

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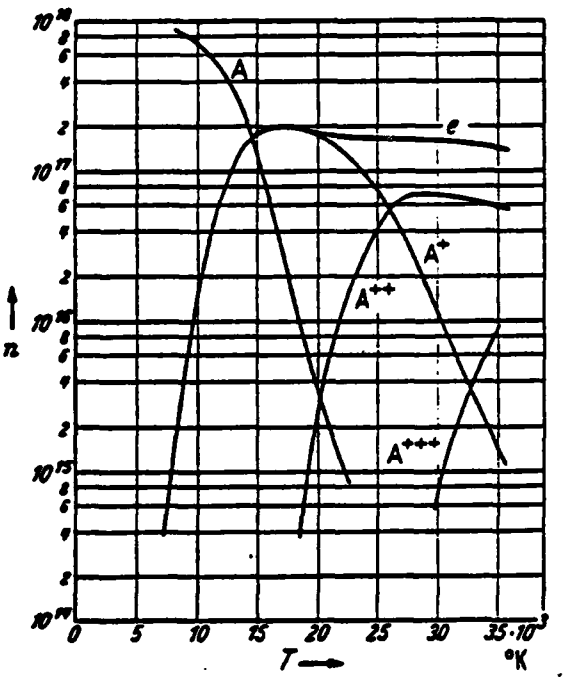
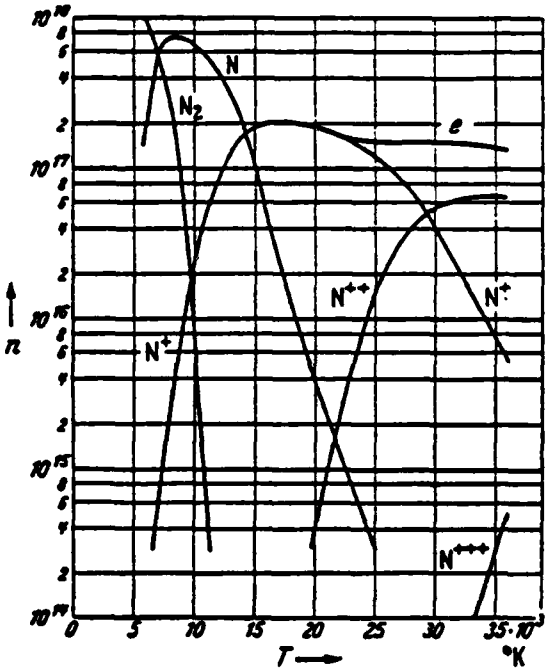
(9) Pearse, R. W. B, and Gaydon, A. G., The Identification of Molecular Spectra, Chapman and Hall, London, 4th Edition, John Wiley and Sons, NY.



Argon



Nitrogen

FIGURE 1. CONCENTRATION OF ATOMIC AND IONIC SPECIES OF ARGON AND NITROGEN IN 200-AMP GAS-TUNGSTEN ARCS AS A FUNCTION OF GAS TEMPERATURE; ATMOSPHERIC PRESSURE[1]

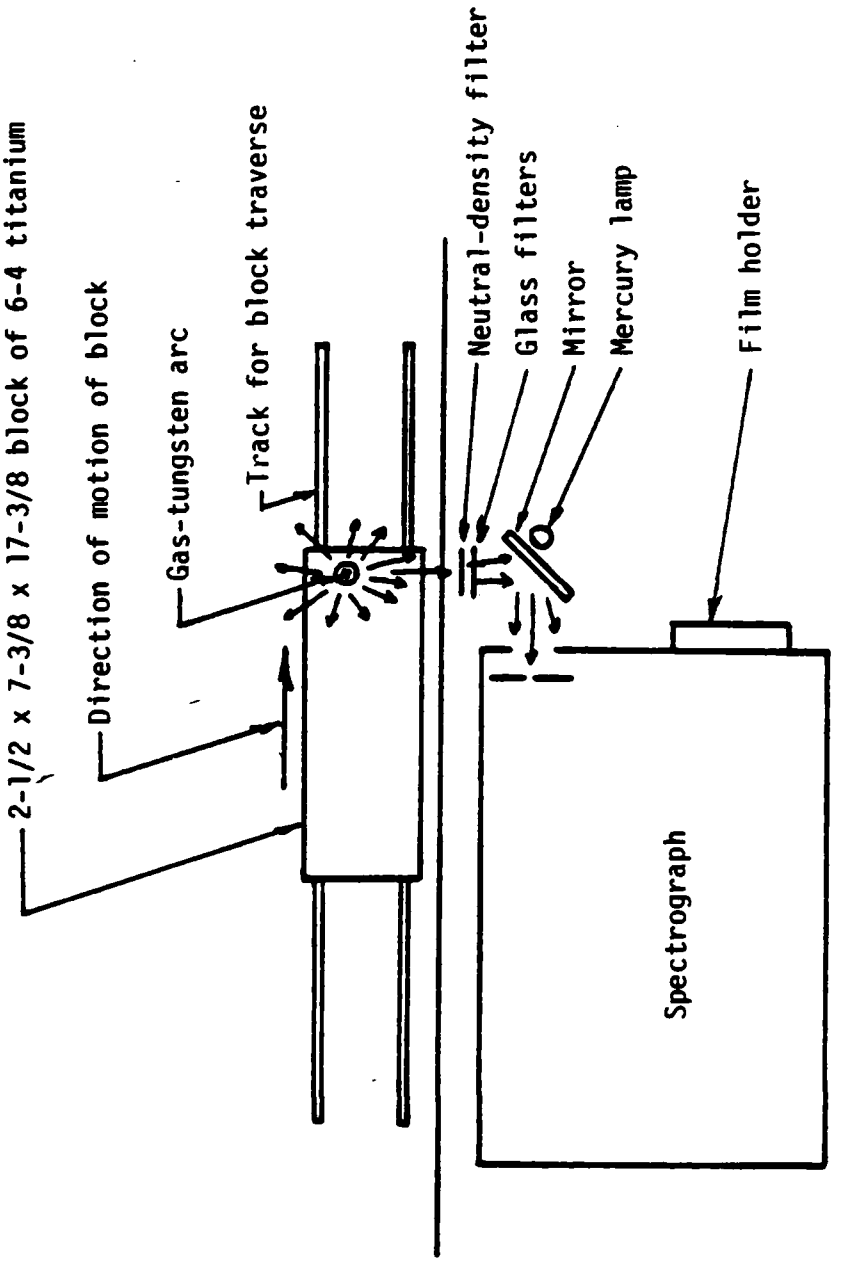


FIGURE 2. SKETCH OF APPARATUS FOR RECORDING ARC SPECTRA

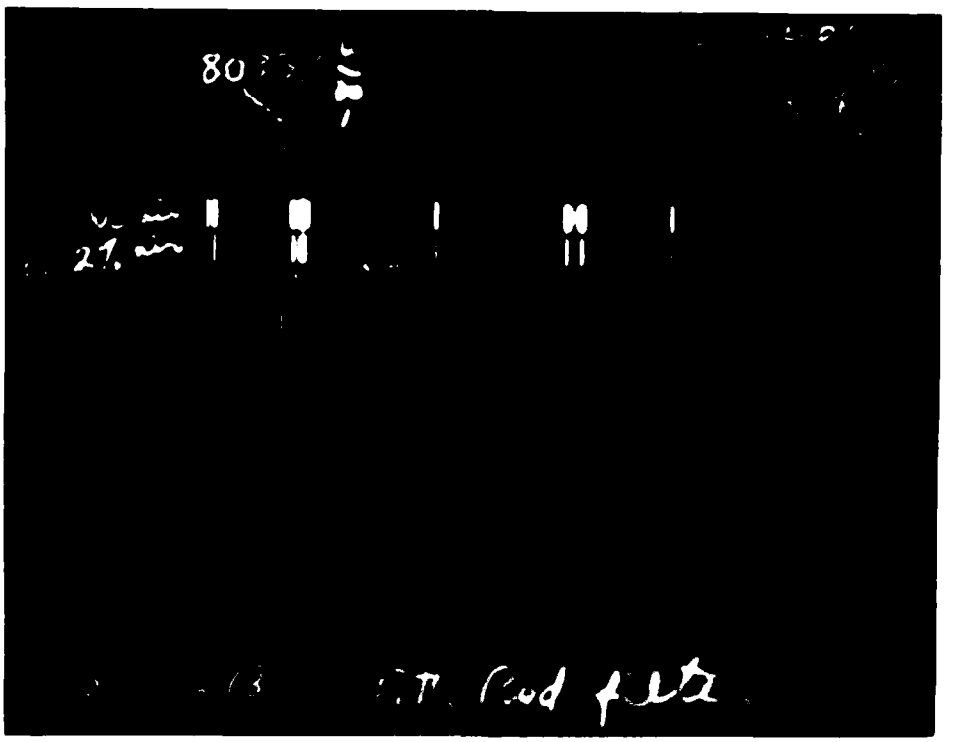


FIGURE 3. PRINT OF TYPICAL SET OF SPECTRA; WAVELENGTH RANGE, 8000 TO 8700 Å. DOTS MARK LINES PRESENT IN 2-PERCENT-AIR SPECTRUM NOT PRESENT IN NO-AIR SPECTRUM

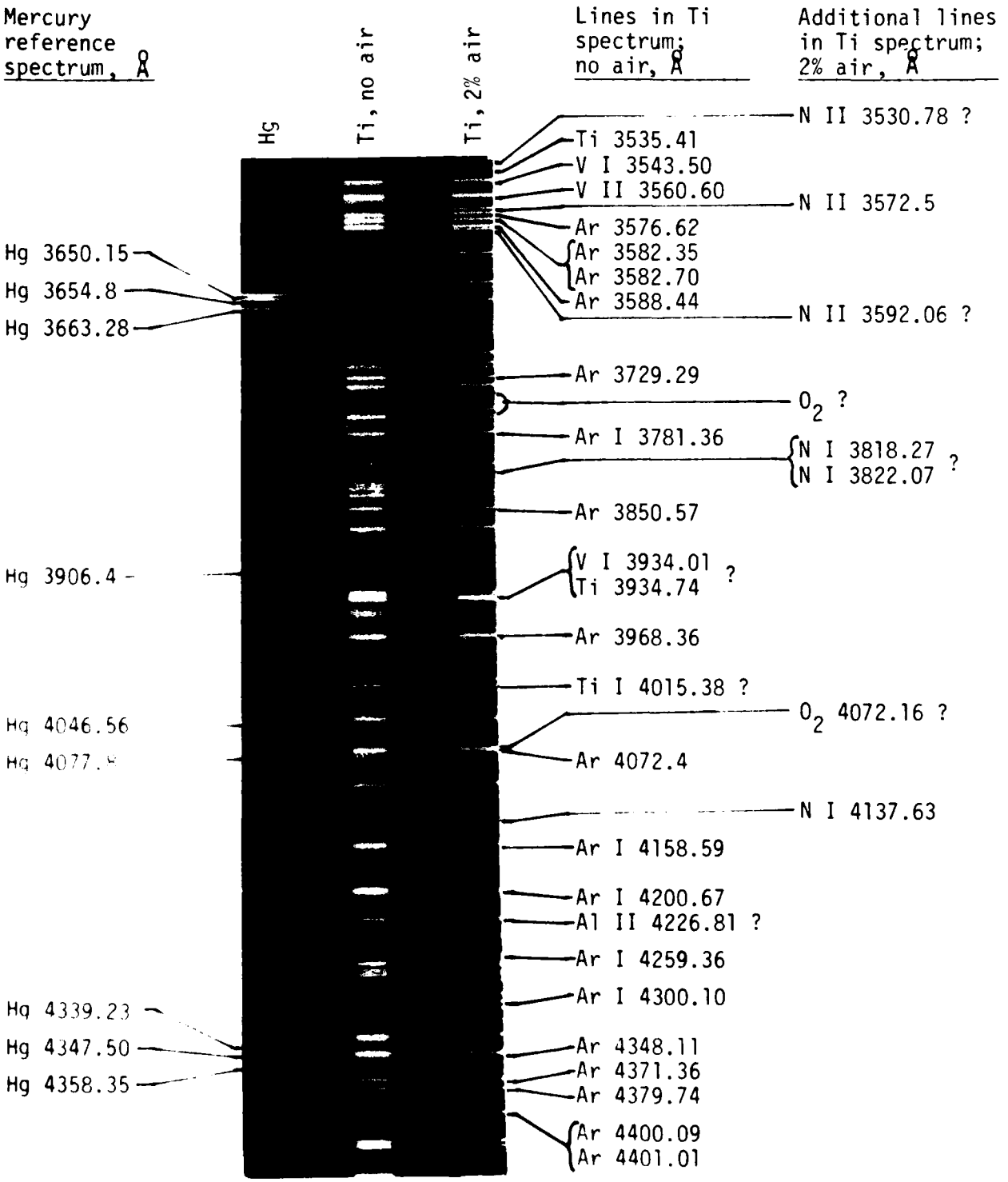


FIGURE 4. SPECTRA OF ARGON-SHIELDED TUNGSTEN ARCS AGAINST 6-4 TITANIUM WITH AND WITHOUT AIR, RANGE: 3530 TO 4401 Å

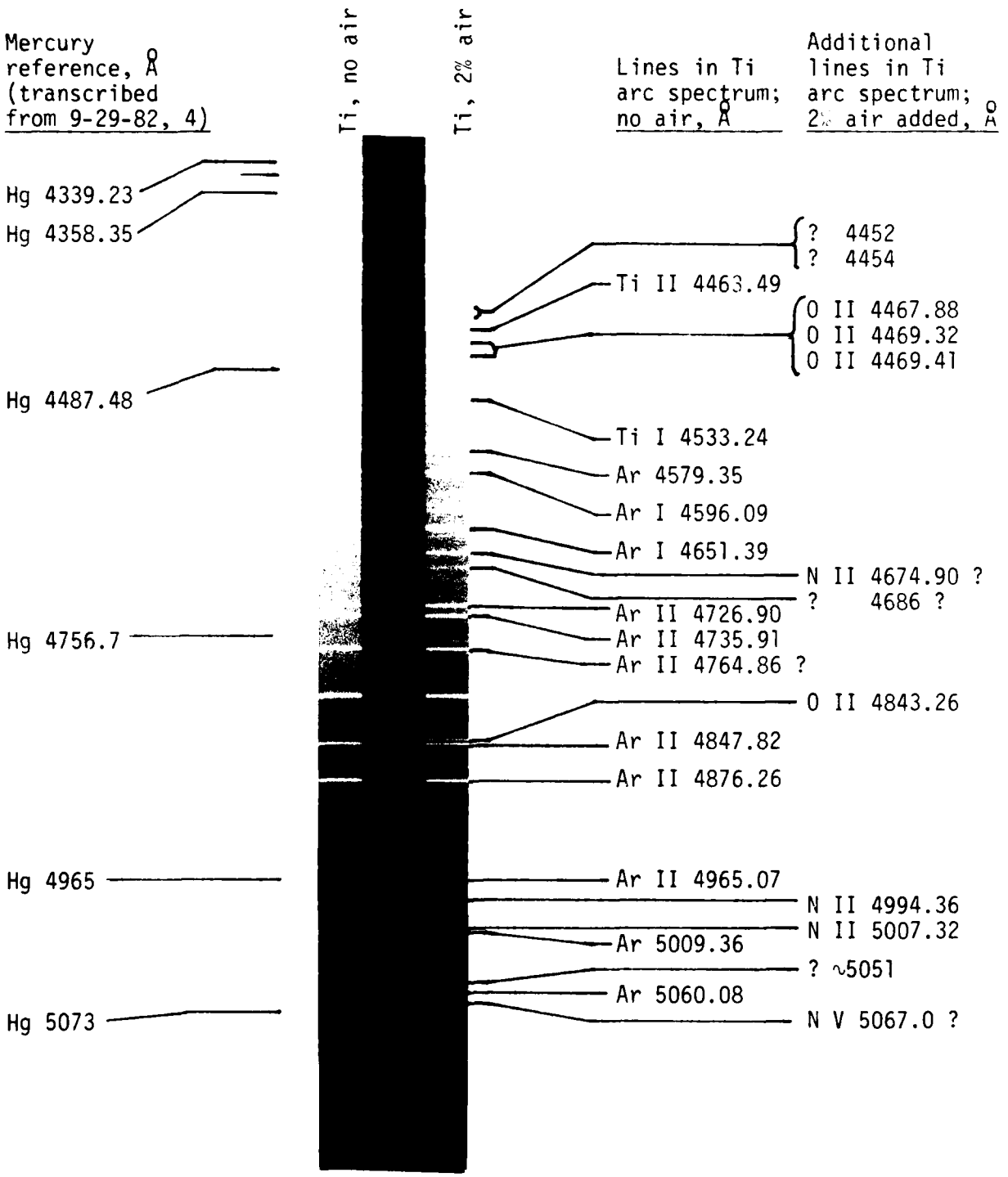


FIGURE 5. SPECTRA OF ARGON-SHIELDED TUNGSTEN ARCS AGAINST 6-4 TITANIUM; WITH AND WITHOUT AIR; RANGE: 4339 TO 5073 Å

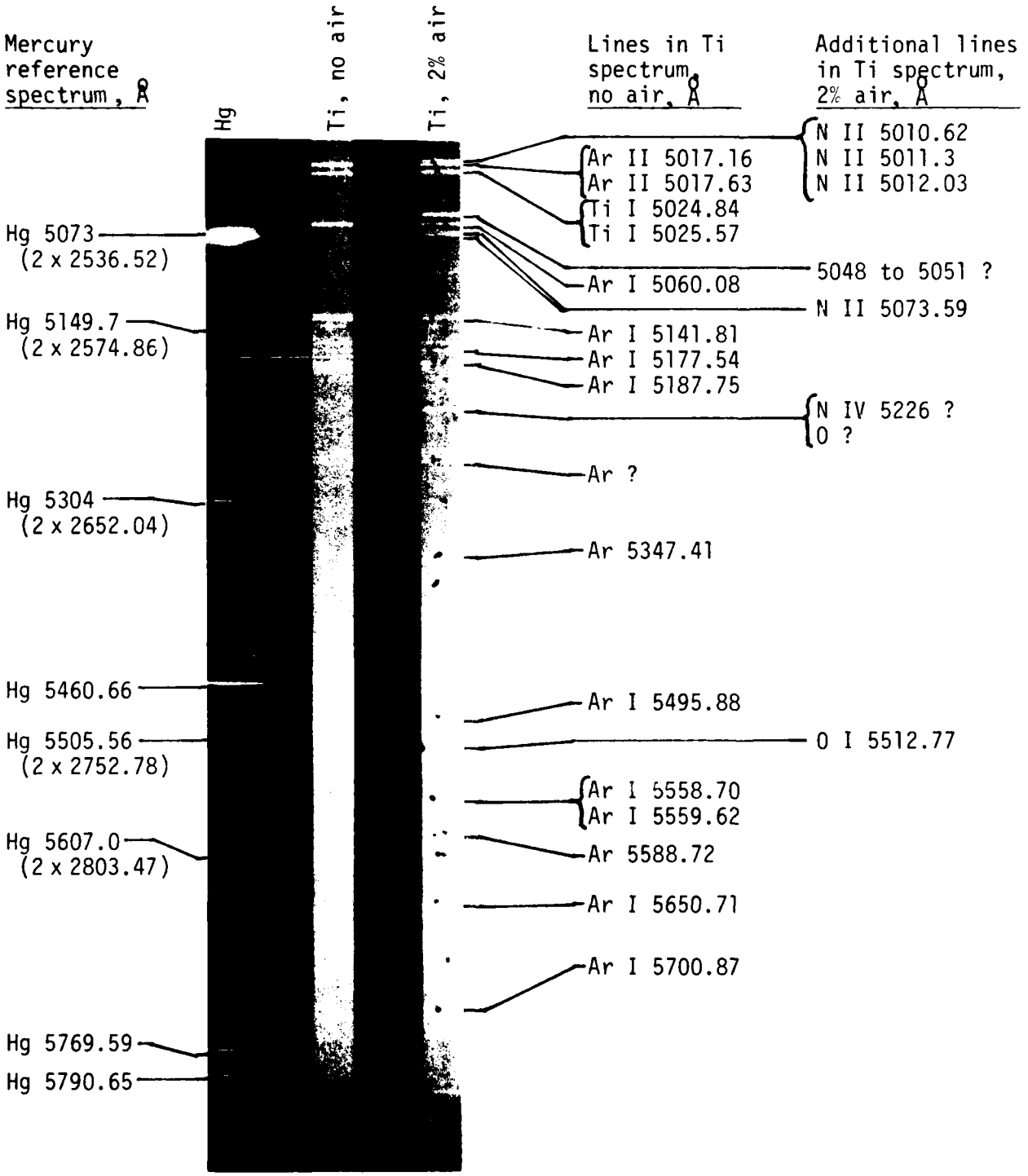


FIGURE 6. SPECTRA OF ARGON-SHIELDED TUNGSTEN ARCS AGAINST 6-4 TITANIUM; WITH AND WITHOUT AIR; RANGE: 5010 TO 5790 Å

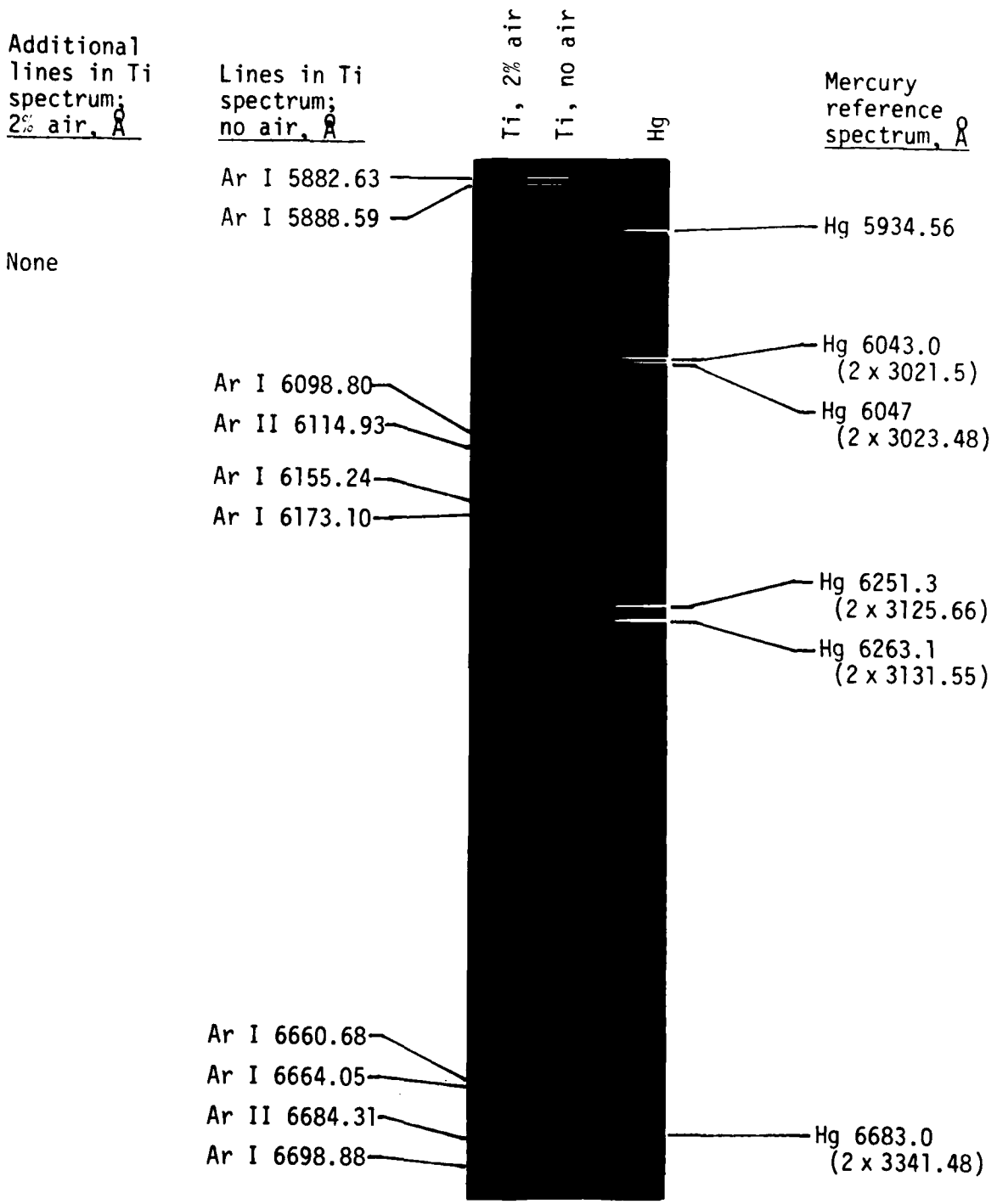


FIGURE 7. SPECTRA OF ARGON-SHIELDED TUNGSTEN ARCS AGAINST 6-4 TITANIUM; WITH AND WITHOUT AIR; RANGE: 5882.63 TO 6683.0 Å

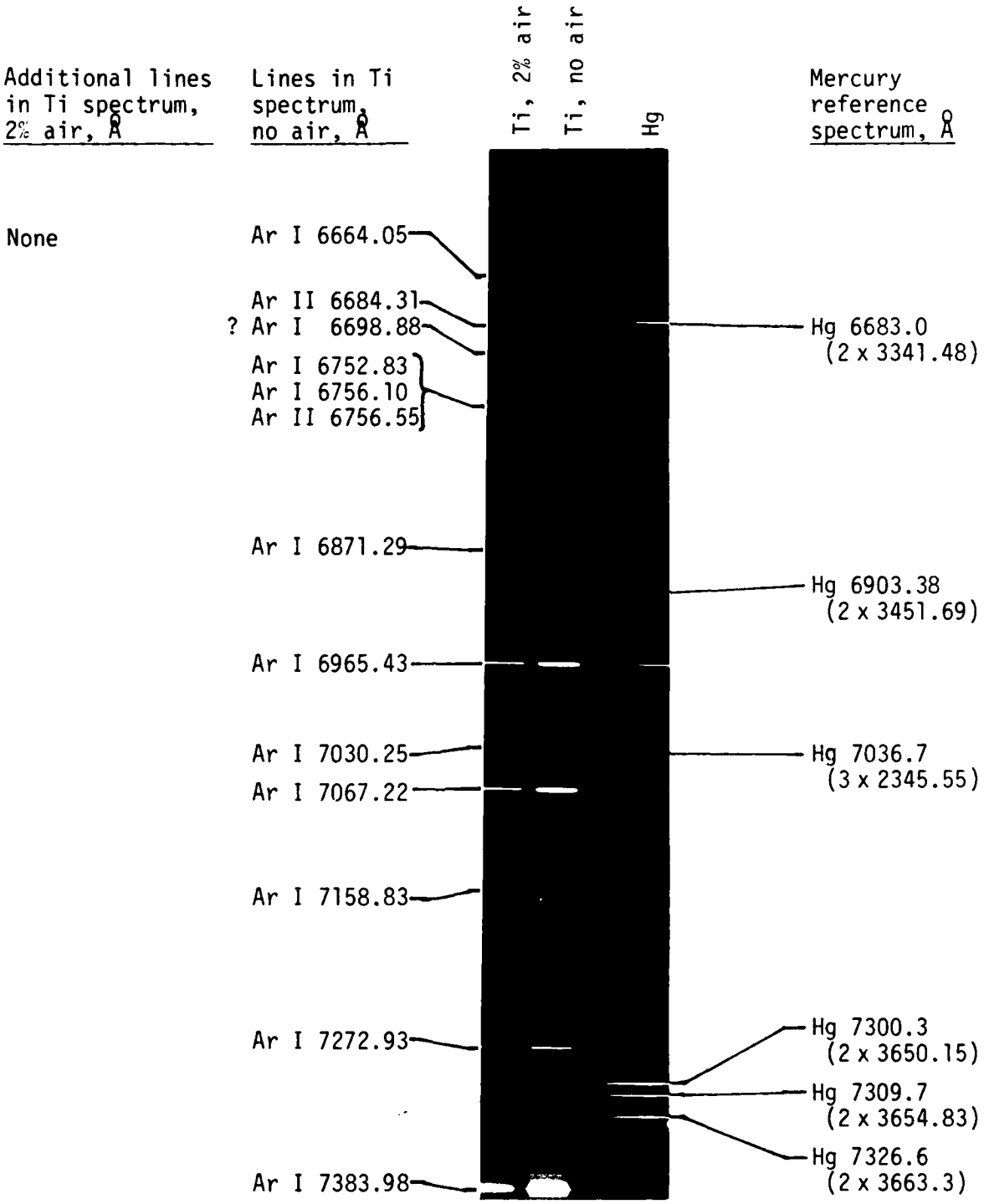


FIGURE 8. SPECTRA OF ARGON-SHIELDED TUNGSTEN ARCS AGAINST 6-4 TITANIUM; WITH AND WITHOUT AIR; RANGE: 6664 TO 7384 Å

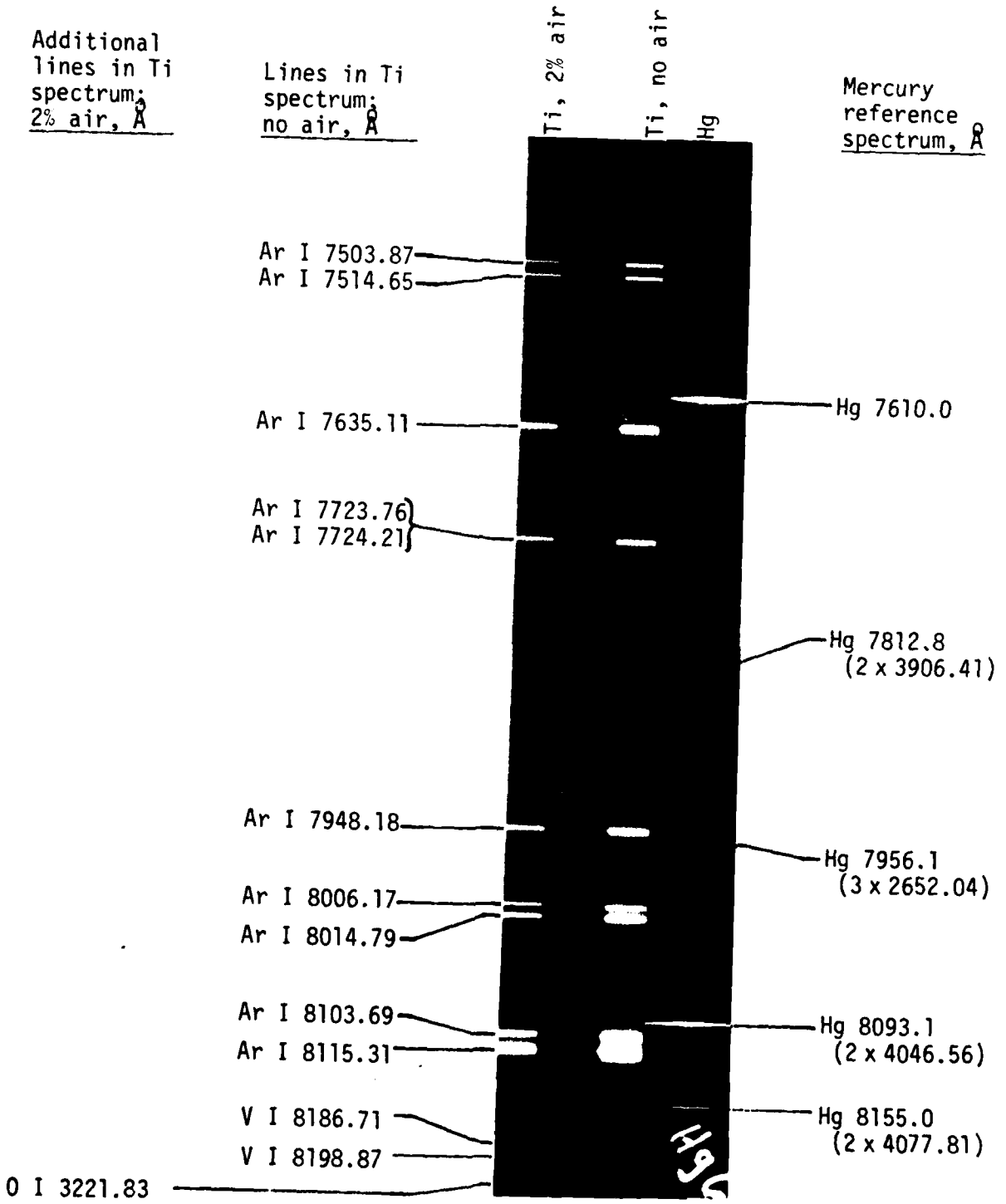


FIGURE 9. SPECTRA OF ARGON-SHIELDED TUNGSTEN ARC AGAINST 6-4 TITANIUM; WITH AND WITHOUT AIR; RANGE: 7503 TO 8188 Å

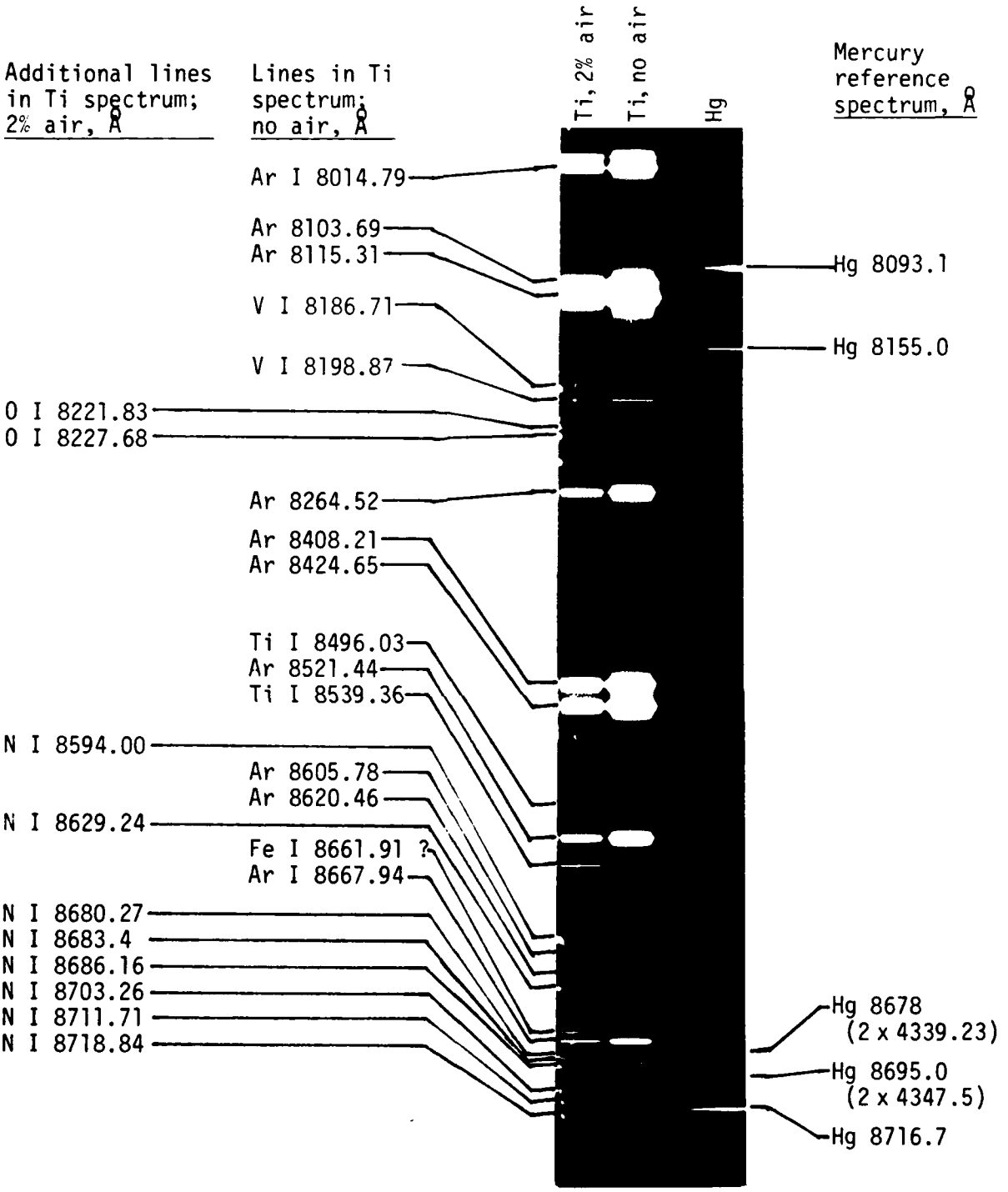
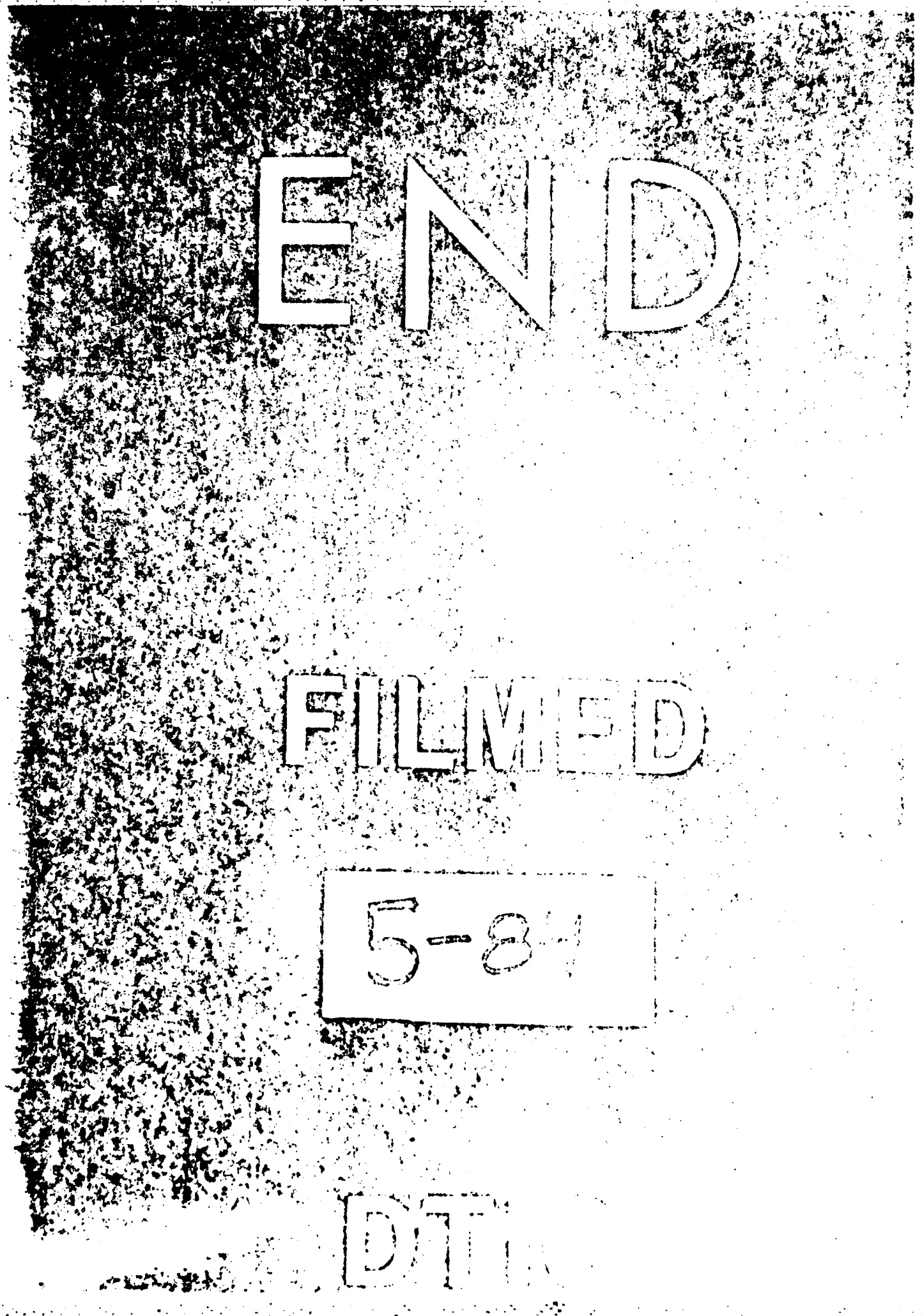


FIGURE 10. SPECTRA OF ARGON-SHIELDED ARCS AGAINST 6-4 TITANIUM; WITH AND WITHOUT AIR; RANGE: 8015 TO 8718.84 Å

TABLE I. SPECTRAL LINES OF NITROGEN OR OXYGEN OF POSSIBLE USE IN ARC MONITORING

Figure Number	Wavelength of Possible Lines, angstroms	Element	Wavelength of Adjacent Interfering Lines, angstroms		Spectral Distance to Adjacent Lines, angstroms	
			Short-Wavelength Side	Long-Wavelength Side	Short-Wavelength Side	Long-Wavelength Side
5	4674.9	N II ?	4651.4	4726.9	23	52
	5051	?	5015	5060.1	36	9
6	5226	N IV ?	5187	~5246	39	20
	5512.8	O I	5495.9	~5536	17	23
10	8221.83	O I	8199	-	23	-
	8227.68	O I	-	8264.5	-	37
	8680.27	N I	8667.9	-	12	-
	8683.4	N I	-	-	-	-
	8703.26	N I	-	-	-	-
	8711.71	N I	-	-	-	-
	8718.84	N I	-	>8740	-	>21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